PHYSICS AND APPLICATIONS OF ELECTRODYNAMIC SPACE TETHERS

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Abstract. Basic effects and dynamical and electrical contact issues in the physics of (electrodynamic space) bare tethers are discussed. Scientific experiments and power-propulsion applications, including a paradoxical use of bare tethers in outer-planet exploration, are considered.

Key words: Spacecraft/Ionosphere interaction; Advanced space power; Advanced space propulsion; Electrodynamic tethers; Ionospheric in-situ experiments.

1. INTRODUCTION

A space tether is a cable or wire connecting two satellites in orbit. Assuming that the tether keeps vertical in a circular orbit, and that tether mass is small compared with end masses m_1 at the bottom and m_2 at the top, the common rotation velocity Ω, in the absence of any other force, is determined by the balance of gravitational and centrifugal forces in the orbital frame,

$$\frac{\Omega^2}{GM_E}(m_2 r_2 + m_1 r_1) = \frac{m_1}{r_1^{\,2}} + \frac{m_2}{r_2^{\,2}}. \tag{1}$$

where M_E is the Earth's mass. For $r_2 - r_1 \equiv L \ll r_1$ one finds

$$\frac{1}{r_2^{\,3}} < \frac{\Omega^2}{GM_E} \approx \frac{1}{(r_1 + L m_2/M)^3} < \frac{1}{r_1^{\,3}}, \tag{2}$$

where $M = m_1 + m_2$ is total mass. The centrifugal force will be greater than the gravitational force for the upper mass m_2, which will thus be subjected to a net force away from the Earth. The opposite holds for the lower mass. This will result in a tension in the tether that clearly makes the vertical orientation a stable one; if tilted, a restoring torque sets up. An orbiting mass m at a radial distance r would experience a 'gravity gradient' force, away from the Earth beyond the radius $r_1 + L\, m_2/M$,

$$3m\Omega^2\,[r - (r_1 + L\, m_2/M)]. \tag{3}$$

If the tether is conductive (ED tether) and carries a current as a result of interaction with the magnetized ionosphere, it will experience a magnetic force [1]-[4].

All missions involving tethers in the past were deployed either in Low Earth Orbit (LEO) or in suborbital flights. The Gemini 11 and 12 missions had 30 m tethers deployed in 1967. NASA deployed 500 m tethers in suborbital flights in joint NASA/Japanese ISAS projects, Charge-1 (1983), Charge-2 (1984) and Charge-2B (1992). These missions had been preceded by NASA's failure to fully deploy 500 m suborbital tethers in 1980 (mission H-9M-69) and 1981 (S-520-2). Joint Canadian NRC/NASA suborbital missions Oedipus A and Oedipus C deployed 958 m and 1 km long tethers in 1989 and 1995, respectively.

In 1992, TSS-1, a 20 km NASA/Italian ASI ED-tether, failed to deploy beyond a fraction of km; in 1996 the similar TSS-1R tether burned on arcing just when fully deployed. In 1993, NASA had deployed the 500 m PMG ED-tether and completed its mission of testing both cathodic and anodic Plasma Contactors in orbit. NASA also had successfully deployed the 20 km (non-ED) tethers SEDS-1 and SEDS-2, in 1993 and 1994 respectively. The Naval Research Laboratory has kept in orbit the 4 km (non-ED) TIPS tether since 1996, but failed to fully deploy the 6 km ATEx in 1999.

2. CONDUCTIVE SPACE TETHERS

In the non-relativistic limit, the Lorentz transformation of the electric field $\bar{E}$ from a frame moving with the local ionospheric plasma to a frame orbiting with the tether is

$$\bar{E}\,(tether\ \ frame) - \bar{E}\,(plasma\ \ frame) \;=\; \left(\bar{U}_{orb} - \bar{U}_{pl}\right)\wedge\bar{B} \;\equiv\; \bar{E}_m . \tag{4}$$

In the highly conductive plasma outside the tether (meters away, typically) the electric field is negligible in the plasma own frame. In the tether frame there is then an outside ('motional') field, $\bar{E}_m$, that can drive a current in the vertical tether. For an insulated tether making electric contact with the plasma through devices at both ends, the current I would be uniform along the tether, and the magnetic force would be

$$\bar{F}_m \;=\; L\bar{I}\wedge\bar{B} \qquad\qquad (\bar{I}\bullet\bar{E}_m > 0). \tag{5}$$

One then has

$$(L\bar{I}\wedge\bar{B})\;\bullet\;(\bar{U}_{orb} - \bar{U}_{pl}) \;=\; -\,\bar{I}\bullet\bar{E}_m\,L < 0, \tag{6}$$

showing electrical power generated in the tether as net intake from the motions of tether and ionophere.

For a simple circular, equatorial, eastward orbit in the LEO region, and a centered, no-tilt dipole model, the geomagnetic field $\bar{B}$ is horizontal and perpendicular to the orbital plane, and points northward in the meridian plane; U_{pl} can be neglected against U_{orb} ($\approx$ 16 U_{pl}); $\bar{E}$ is vertical and upward; and $\bar{F}_m$ points westward and drags the tether and its spacecraft. One then has

$$E_m = U_{orb}B_{\perp}, \qquad F_m(\mathrm{drag}) = LIB_{\perp}, \qquad W_m = F_mU_{orb} = IE_mL, \tag{7}$$

where W_m is the power taken from the orbital motion by the magnetic drag. In general, the magnetic field will have components both vertical and parallel to $\bar{U}_{orb}$, in addition to $B_{\perp}$, which is perpendicular to the orbital plane. This results in a component of the motional electric field $E_{m\perp}$, which will just produce a negligible potential difference across the thin cross section of the tether, and will not affect charge collection, to be considered in the next section; a typical value of any component of the motional field is

7.5 km/s × 0.2 gauss = 0.15 V/m or 150 V/km. Current will still be driven by the field $U_{orb}B_{\perp}$ [5], [6].

The magnetic power is still given as $W_m = LIB_{\perp}U_{orb}$ too, but the magnetic force now presents a component $F_{m\perp}$ that pushes the tether off the orbital plane. The magnetic torque can result in certain ('skip-rope') instability. Keeping the centered, no-tilt dipole magnetic model but taking a circular orbit of non-zero inclination i_{orb}; taking current constant throughout in time though variable along the tether, as considered in the next section; and assuming a dumbell dynamic model, with end masses m_1 and m_2 and a (straight) tether of mass m_t, the system exhibits a coupled in-plane/off-plane periodic motion, its period being the orbital one. This motion is unstable, however, the growth rate (per period) being $\cos i_{orb} \sin^2 i_{orb} \times \varepsilon^3 \times \pi/9$. Here the dimensionless factor ε is

$$\varepsilon = \int_0^L \frac{4 B_{eqE} R_E{}^3 I(h)}{G M_E M} \frac{\cos^2 \phi_m - h/L}{\sin^2 2\phi_m - 2m_t/3M} \frac{dh}{L}, \qquad \tan^2 \phi_m = \frac{2m_2 + m_t}{2m_1 + m_t} \quad (8)$$

where $M = m_1 + m_2 + m_t$; h is distance along the tether from its top; and R_E and B_{eqE} are the Earth's radius and the magnetic field at the equator on Earth's surface. The growth rate depends on the mass distribution, and sharply on the current [7].

The magnetic force on a tether requires no ejection of propellant, as opposite rockets or electrical thrusters. Plasma devices presently used for electric contact at the cathodic end do eject (Xenon) expellant along with electrons. Expellant is consumed, however, at an extremely low rate, as later discussed; however, because of its own mass and related hardware mass, use of a tether in a variety of applications will prove more convenient the longer the mission. The bottleneck in such applications, anyway, is the anodic-contact issue: how to efficiently collect electrons from the rarefied ionosphere. The TSS-1 and TSS-1R tethers carried a conductive sphere of 1.6 m diameter acting as passive collector. Space charge keeps the electric field to a sheath around the sphere (ionospheric Debye length, λ_D, is a fraction of cm), and the geomagnetic field guides electrons along field lines (electron gyroradius, l_e, is a few cm); this strongly limits the current reaching such spherical collector [8], [9].

As a way out, it was proposed to strip the tether off its insulation and use its positively polarized (anodic) segment as electron collector; because of the enormous length-to-radius ratio (~ 10^6) each point in the tether would collect current as a cylindrical Langmuir probe uniformly polarized at the local bias ΔV. Both magnetic force F_m and power W_m would now involve the current averaged over the tether length, I_{av} (less than the full current ejected at the HC, I_{HC}). A kms-long segment would provide a large collecting area even for a radius R of a few mm; also, a bare tether, by self-adjusting the length of its anodic-segment, proves fairly insensitive to regular drops of plasma density in orbit. Further, both Debye shielding and magnetic guiding might not apply for such thin cylinders. There is a basic difference between collection in spherical and in cylindrical geometry in this respect [10].

3. BARE-TETHER ELECTRON COLLECTION

The electron current to a cylindrical or spherical Langmuir probe at rest in a collisionless, unmagnetized, Maxwellian plasma of density N_∞ and temperatures T_e and T_i, may be written as $I = I_{th} \times$ *a function of* $e\Delta V/kT_e$, R/λ_D, T_i/T_e, where I_{th} is random current, and ΔV is probe bias. In general, determining electron trajectories to find I requires solving Poisson's equation for the potential $\Phi(r)$, with $\Phi = \Delta V > 0$ at $r = R$, $\Phi \to 0$ as $r \to \infty$. The Boltzmann law applies, at high bias, to the density of repelled ions except where fully negligible anyway. Since the distribution function of electrons, all originated at infinity, is conserved along trajectories, its value at given $\bar{r}, \bar{v}$ will be the undisturbed Maxwellian f_M if their trajectory connects back to infinity, and zero otherwise. For the cylinder, the density $N_e(r)$ is an integral of f_M over all positive values of energy $E \equiv \frac{1}{2}m_e(v_r^2 + v_\theta^2) - e\Phi(r)$ (once for radial velocity $v_r < 0$, and again for $v_r > 0$), and an allowed range of angular momentum $J \equiv m_e r v_\theta$ that is both E and r dependent:

i) For an E-electron incoming at r the range of integration is $0 < J < J_r^*(E) \equiv$ *minimum* $[J_{r'}(E)\ ;\ r \le r' < \infty]$, where $J_r^2(E) \equiv 2m_e r^2[E + e\Phi(r)]$. Condition $v_r^2 \ge 0$ requires just $J \le J_r(E)$; the electron will only reach r, however, if $v_{r'}^2$ is positive throughout the range $r < r' < \infty$.

ii) For an E-electron outgoing at r the range of integration is $J_R^*(E) < J < J_r^*(E)$, electrons in the range $0 < J < J_R^*(E)$ having disappeared at the probe.

The density N_e as a functional of $\Phi(r)$, and the current I, are then

$$\frac{N_e}{N_\infty} = \int_0^\infty \frac{dE}{\pi k T_e} \exp\left(\frac{-E}{kT_e}\right)\left[2\sin^{-1}\frac{J_r^*(E)}{J_r(E)} - \sin^{-1}\frac{J_R^*(E)}{J_r(E)}\right], \tag{9}$$

$$\frac{I}{I_{th}} = \frac{2}{\sqrt{\pi}} \int_0^\infty \frac{dE}{kT_e} \exp\left(\frac{-E}{kT_e}\right) \frac{J_R^*(E)}{\sqrt{2m_e R^2 kT_e}}. \tag{10}$$

With $J_R^*(E) \le J_R(E)$, maximum current occurs if the equality holds for $0 < E < \infty$. This is the orbital-motion-limited (OML) regime, the ratio I_{OML}/I_{th} then depending only on $e\Delta V/kT_e$; at high bias,

$$I_{OML}/I_{th} = \sqrt{4e\Delta V/\pi kT_e}. \tag{11}$$

For a sphere, one similarly has

$$\frac{N_e}{N_\infty} = \int_0^\infty \frac{dE}{kT_e} \exp\left[\frac{-E}{kT_e}\right] \frac{J_r(E) + \sqrt{J_r^2(E) - J_R^{*2}(E)} - 2\sqrt{J_r^2(E) - J_r^{*2}(E)}}{\sqrt{\pi}\sqrt{2m_e r^2 kT_e}}, \tag{12}$$

$$\frac{I}{I_{th}} = \int_0^\infty \frac{dE}{kT_e} \exp\left[\frac{-E}{kT_e}\right] \frac{J_R^{*2}(E)}{2m_e R^2 kT_e}. \tag{13}$$

The 3D-OML current is $I_{OML}/I_{th} = 1 + e\Delta V/kT_e$. At high bias and for probes of equal area, this current is much greater than the 2D-OML current but is never reached.

The $\Phi(r)$-dependent structure of the r-family of straight lines $J^2 = J_r^2(E)$ in the J^2-E plane determines the functions $J_r^*(E)$ and $J_R^*(E)$, which in turn determine N_e for use in Poisson's equation. Since the slope $dE/dJ^2 = 1/2m_e r^2$ varies monotonically with r, it suffices to have $J_r^*(0) = J_r(0)$ for $J_r^*(E) = J_r(E)$ to apply throughout the entire range $0 < E < \infty$, at any particular r. On the other hand, $J_r^2(0)$ varies as $r^2\Phi(r)$ which proves non-monotonic; this results in a complex r-family structure. The OML condition, however, requires the potential to just satisfy $J_R^*(0) = J_R(0)$, i.e. $r^2\Phi(r) > R^2\Delta V$ throughout the range $R < r < \infty$. For a cylinder, faraway quasineutrality $N_e \approx N_i$ shows a behavior $\Phi \sim 1/r$. Moving toward the probe, $r^2\Phi(r)$ decreases to a minimum (lying far from the probe for high bias and $R \sim \lambda_D$); the quasineutral solution remains valid up to a point where $-d\Phi/dr$ diverges, marking the sheath boundary. Within the broad sheath $r^2\Phi(r)$ reaches a large maximum (at minimum N_e) before again dropping to $R^2\Delta V$ at the probe.

If R exceeds some maximum radius $R_{max} \sim \lambda_D$, the $r^2\Phi(r)$ minimum lies below $R^2\Delta V$, the ratio I/I_{OML} then dropping below 1, and decreasing with increasing R/R_{max}. For $R > R_{max}$, trajectories that hit the probe within some range of glancing angles are unpopulated: the probe being attractive, they come, not from the background plasma, but from other points on the (non-emissive) probe, after having turned back in the far field. For a sphere, quasineutrality yields a faraway behavior $\Phi \sim 1/r^2$ with $r^2\Phi(r)$ always below $R^2\Delta V$; a large sphere follows a thin-sheath behavior, $r^2\Phi$ keeping low for almost the entire radial range, only rising above $R^2\Delta V$ near the probe. For a small sphere, $r^2\Phi$ rises above $R^2\Delta V$ at large distances (thick sheath) [11], [12].

The OML current law for a cylinder is very robust. The ratio I_{OML}/I_{th} is independent of R/λ_D and T_e/T_i values over a large domain in parameter space. It holds independently of the ion distribution function, and in the high-bias case it holds independently of the particular electron distribution if isotropic. Further, the OML law does not require a rotationally symmetric potential. Laframboise and Parker showed that it is valid independently of cross-section shape if convex enough [13], currents to two probes being equal for equal bias, length and cross-section perimeter p, with OML current density uniform over probe surface independently of shape. The high-bias current, Eq. (11), is thus best written as

$$I_{OML} = L\frac{p}{\pi}eN_\infty\sqrt{\frac{2e\Delta V}{m_e}} \qquad (e\Delta V >> kT_e). \qquad (14)$$

For any convex cross-section there is some equivalent radius $R_{eq} \neq p/2\pi$ for using R_{eq}/R_{max} in the non-OML results for round wires. Because of the high bias, the space charge affects negligibly a region around the probe where the Laplace equation holds and reaching where $\nabla\Phi$ becomes radial. This allows to determine the radius R_{eq} by solving the Laplace equation between the contour of the given cross section, where $\Phi = \Delta V$, and a circle of any radius $r_\infty >> p$ where Φ vanishes; the Laplace equation filters out to the far field all information on shape except the equivalent radius R_{eq}. This classical problem in transmission lines yields the capacity per unit length between two cylinders as $C_l \approx 2\pi\varepsilon_0/\ln(r_\infty/R_{eq})$. For a thin tape, $R_{eq} = p/8$.

The OML law breaks down for non-convex shapes as an effect independent of size and related to the behavior of the potential near the probe. For a thin tape, one finds that trajectories that would hit any point on it within some (very narrow) range of glancing angles are unpopulated: they would had come from other points on the tape, having kept close to it throughout. This current reduction holds no matter how small the probe. For a tape, shape failure is quite weak, the current lying within one per cent of the OML value. The reduction of current below the OML value for small cross sections are substantial for the booms of Sec.8, which present definitely concave segments, but the OML law may still be used if p is replaced by the perimeter p_{eq} of the minimum-perimeter (convex) envelope of the cross section, made of segments of the actual cross section and straight connecting segments [14].

The above results apply to unmagnetized plasmas at rest, with no electrons trapped in bound trajectories. As regards U_{orb} effects, the 2D-OML law should still hold because that mesothermal speed barely breaks electron isotropy. Due to ion-ram effects, however, a substantial trapped-electron population is required to keep quasineutrality over a large wind-side region; collisional trapping rates prove too slow to be of consequence [11] but 'adiabatic' collisionless trapping [15] might do. Geomagnetic effects might in principle break the 2D-OML law because of 3D considerations. There exists, however, an upper (*Parker-Murphy*) bound to current to a cylinder in a magnetized plasma [8]; at high bias that bound reads

$$I_{PM} \approx I_{OML}\sqrt{2/\pi}\times l_e/R. \tag{15}$$

Clearly, for $R << l_e$ this bound is well above I_{OML}; the geomagnetic field is then expected to hardly affect the current. Joint geomagnetic/ram-motion effects are hard to determine. Results from numerical simulations [16] and laboratory tests [17] have been inconclusive.

4. DIMENSIONLESS PARAMETERS

Current and bias profiles along the tether are respectively determined by the OML collection law, and by the difference between motional field E_m and (ohmic) voltage drop-rate inside the tether. For an eastward-orbiting satellite and current driven by the field E_m, the profile equations for a top anodic segment $(\Delta V > 0)$ collecting electrons are

$$\frac{dI}{dh} = \frac{p}{\pi}eN_\infty\times\sqrt{\frac{2e\Delta V}{m_e}}, \tag{16}$$

$$\frac{d\Delta V}{dh} = -E_m + \frac{I}{\sigma_c A}, \tag{17}$$

where σ_c and A are tether conductivity and cross-section area, h is again distance along the tether from its top, and I is here the electron current, flowing downwards opposite the conventional current. (Most of) the cathodic $(\Delta V < 0)$ segment below is insulated to make fully negligible the small ion current that would be collected otherwise. *Equations (16, 17) can be written in dimensionless form by introducing a characteristic length* L^* that gauges ohmic effects for bare tethers,

$$L^*\frac{p}{\pi}eN_\infty\times\sqrt{\frac{2eE_mL^*}{m_e}} \equiv \frac{3}{4}\frac{E_mL}{Z_t} = \frac{3}{4}\sigma_cE_mA, \tag{18}$$

where $Z_t \equiv L/\sigma_c A$ is tether resistance and E_mL/Z_t is the short-circuit current.

Dimensionless current, bias, and distance from top can then be defined as

$$i \equiv \frac{I}{\sigma_cE_mA}, \qquad \varphi \equiv \frac{\Delta V}{E_mL^*}, \qquad \xi = \frac{h}{L^*}. \tag{19}$$

Profiles $i(\xi)$ and $\varphi(\xi)$ will depend on the ratio L/L^*, which varies as $L/R^{2/3}$ and as $L/\delta^{2/3}$ for a round wire of radius R and a thin tape of thickness δ respectively; convenient large values of that ratio (corresponding to negligible collection impedance) are thus easier to attain with tapes. Profiles also depend on a number of other dimensionless ratios according to the operating mode: Z_l/Z_t in the power-generation mode, Z_l being the useful load impedance; and $W_e/\sigma_cE_m^2AL$ and L_i/L in the thrusting mode, W_e being the electrical power supplied and L_i an insulated anodic segment of tether.

Effects of the magnetic field created by the tether-current itself, reducing collection, are found to be weaker the lower a dimensionless parameter, $K_s \propto R^{5/3}$ and $K_s \propto \delta^{2/3}\times$ *tape width* for round wires and thin tapes respectively; those effects are again clearly weaker for tapes [18], [19]. The overall tether-system mass is also characterized by a dimensional parameter $\rho/\sigma_cE_m^2$, reaching a minimum for aluminum,

$$\frac{\rho}{\sigma_c E_m{}^2} \approx 3.43 \times \left(\frac{150V/km}{E_m}\right)^2 \frac{kg}{kw},$$

which can be compared to values of a parameter β (kg/kw) characterizing different space power systems (solar arrays, fuel cells, RTG's); here ρ is tether density.

5. POWER GENERATION MODE

Long space missions use arrays of photovoltaic cells that profit from free solar power, whereas batteries serve as primary sources of electrical power for very short missions, say, less than one day, and fuel cells typically serve for missions of 1-2 weeks. It comes out that for longer periods, with solar power not available, power generation by a combination ED-tether/rocket, with the tether providing electrical power and the chemical rocket providing thrust to compensate the magnetic drag on the tether, proves more efficient as regards fuel consumption than direct power generation in a fuel cell [5], [6].

A tether in the generation mode provides power $W_e = \eta_g W_m$ $(W_m = F_m U_{orb})$, where η_g is the efficiency in taking energy from the orbital motion into useful energy at some electrical load Z_l in the tether circuit. Rocket thrust must equal the magnetic drag to keep the orbit stationary. With thrust given as $\dot{m}\, v_{exh}$ ($\dot{m}$ and v_{exh} being propellant mass-flow-rate and velocity at rocket exhaust), the magnetic power is $W_m = \dot{m} v_{exh} U_{orb}$, which is clearly larger than the rocket output power, $\frac{1}{2}\dot{m} v_{exh}{}^2$: a satellite in LEO orbit has a velocity $U_{orb} \approx 7.5$ km/s, whereas $\frac{1}{2}v_{exh}$ for LOX-LH_2 can be only as large as 2.25 km/s (specific impulse $\approx$ 460s), say.

How can one have W_m larger than rocket power output, which is the sole source of energy? Consider the standard rocket equation, allowing for a drag F_m,

$$-F_m = M\frac{dU}{dt} + \dot{m}\,(-v_{exh}) \equiv \frac{d}{dt}MU + \dot{m}\,(U - v_{exh}) \qquad (20)$$

with M the full system mass and $dM/dt = -\dot{m}$. The energy equation resulting from Eq. (20) is

$$-UF_m + \frac{1}{2}\dot{m} v_{exh}{}^2 = \frac{d}{dt}\frac{1}{2}MU^2 + \frac{1}{2}\dot{m}(U - v_{exh})^2. \qquad (21)$$

Equations (20, 21) show that for $F_m = 0$ there is no source of momentum if one accounts for both rocket and exhaust fuel, whereas the rocket output power does provide a source of energy. The left-hand-side of Eq. (21) can be negative if the instantaneous rocket energy decreases fast enough with mass M; for $U = U_{orb} = constant$, Eq. (21) does recover the result $W_m = \dot{m} v_{exh} U_{orb}$.

Since the fuel cell, however, uses a much lighter power plant, the combined tether/rocket system should be preferred as regards overall mass only for periods long enough that total fuel consumed by the cell exceeds the tether power-plant. With the mass required by the cell being basically fuel mass whereas both tether and rocket-fuel masses contribute to the combined system, that condition reads

$$\dot{m}_{fc}\,\tau > \alpha_t \rho A L + (1 + \alpha)\dot{m}\,\tau. \qquad (22)$$

Both systems must provide a given electrical power W_e during a given time τ,

$$\eta_{fc}\,\dot{m}_{fc} \times \tfrac{1}{2} v_{fc}{}^2 = W_e = \eta_g I_{av} E_m L = \eta_g \dot{m}\, v_{exh} U_{orb},$$

where I_{av} is the current averaged over the tether length. The energy per unit fuel-mass liberated in a LOX-LH_2 cell is about 1.25×10^7 J/kg, which we formally wrote for convenience as '$\frac{1}{2} v_{fc}^2$' with $v_{fc} \approx 5$ km/s; $\dot{m}_{fc}$ and η_{fc} (about 0.75) are cell mass-flow-rate and efficiency respectively; and the fraction $\alpha \leq 0.2$, and the factor $\alpha_t \sim 2$-3, typically, account for tankage and plumbing, and for tether-related hardware (deployer, end-mass).

It follows from (22) that the tether/rocket system will save mass for times

$$(\eta_g - b)\tau > \frac{\tau_g}{9 i_{av}}, \qquad \tau_g \equiv \frac{9\alpha_t \eta_{fc} \rho v_{fc}^2}{2\sigma_c E_m^2} \qquad b \equiv \frac{(1+\alpha)\eta_{fc} v_{fc}^2}{2 v_{exh} U_{orb}} = \frac{1}{3}. \quad (23)$$

Minimum times correspond to a maximum of $(\eta_g - b) \times i_{av}$. Both current and efficiency increase with the ratio L/L^* but vary with Z_l/Z_t in opposite ways, reflecting the power/efficiency trade-off common to electrical generators. For a tether insulated over most of its cathodic segment, and convenient, large L/L^*-values, one has $i_{av} \approx 1 - \eta_g$, (23) making times minimum for a Z_l/Z_t ratio such that $\eta_g = 2i_{av} = 2/3$. The condition for a tether/rocket system to save mass then reads

$$\tau > \tau_g \approx 0.523\, \alpha_t \times (150 \text{ Vkm}^{-1} / E_m)^2 \textit{ weeks}. \qquad (24)$$

6. DEORBITING MODE

The Low Earth Orbit region in space around Earth, from 200 km to 2000 km altitude, has become crowded with dead satellites and spent upper stages of rockets. How to deorbit a satellite at the end of its operational life is now an issue in space technology. An ED-tether using no load, in order to maximize the current, and no drag-balancing rocket, is well suited to this task. An Ion Thruster powered by a solar array, which the tether does not require, would be the alternative to tethers. Both systems should provide a given total impulse for deorbiting, $F\tau$, which is determined by mission parameters (mass and orbital altitude of the satellite), within a maximum allowed time τ_{max} [20], [21].

The condition for the tether to save mass would then be

$$(1+\alpha)\dot{m}_{IT}\tau + \beta W_e > \alpha_t \rho A L, \qquad (25)$$

where the mass per unit power β in the power subsystem of the Ion Thruster accounts for PPU and thruster iself and may account for the array; β values then range from a few kg/kw to a few tens of kg/kw. The required power is proportional to the mass-flow-rate $\dot{m}_{IT}$,

$$W_e = \tfrac{1}{2}\, \dot{m}_{IT} v_{IT}^2 / \eta_{IT},$$

with exhaust velocity v_{IT} and efficiency η_{IT} taking approximate values 30 km/s and 0.65, respectively [22].

One may easily verify that system mass for either tether or Ion Thruster will be lower the longer the mission. We may then take mission duration τ ($= \tau_{max}$), and thus thrust F, equal for both systems,

$$\dot{m}_{IT} v_{IT} = F = I_{av} L B_\perp, \qquad (26)$$

condition (25) above now reading

$$(1+\alpha)\tau + \tau_{IT} \;>\; \frac{\tau_d}{i_{av}} \tag{27}$$

where

$$\tau_d \;\equiv\; \alpha_t \frac{\rho U_{sat} v_{IT}}{\sigma_c E_m{}^2} \;\approx\; \frac{8}{3}\tau_g \;\approx\; 1.39\alpha_t \times \left(\frac{150V/km}{E_m}\right)^2 \textit{weeks}. \tag{28}$$

The time τ_{IT} characterizing the Ion-Thruster system is such that consumed fuel mass equals the power-subsystem mass,

$$\tau_{IT} \;\equiv\; \frac{\beta v_{IT}{}^2}{2\eta_{IT}} \;\approx\; 1.14 \times \beta \left(\frac{kg}{kw}\right) \textit{weeks}. \tag{29}$$

The dimensionless average current reaches a maximum, $i_{av} = 1$, at large L/L^*. Using a tether will thus save mass for deorbiting times satisfying condition

$$(1+\alpha)\,\tau + \tau_{IT} > \tau_d. \tag{30}$$

This condition is satisfied for all times for the higher values of β, and for times beyond a few weeks for the lowest β values.

7. THRUSTING MODE

If powered, as an Ion Thruster, an ED tether could carry current opposite the direction driven by the motional field E_m, and thus produce thrust instead of drag. Both power source and Hollow Cathode will lie at the top, with electron current flowing upwards. Equations (16, 17) hold if h is now distance from tether bottom and the right-hand-side of (17) reads $E_m + I/\sigma_c A$. Bias and current profiles will now depend on ratios L/L^* and $W_e/\sigma_c E_m{}^2 AL$, and on the insulated length fraction L_i/L. With ΔV increasing monotonically from bottom to top, the average current (which determines the magnetic force) would be a small fraction of the current at top (which determines the supply power required), and result in low thrust efficiency if the tether was fully bare ($L_i = 0$).

A term accounting for the mass of the power subsystem, βW_e ($\equiv \beta F_m U_{orb}/\eta_t$), where $\eta_t \equiv W_m/W_e$ is the thrust efficiency, must be added to the mass of the tether. As for deorbiting, both systems must provide a given mission impulse, $F\tau$, within a maximum allowed time. This again leads to separate conditions of equal thrust F and equal mission duration τ. The condition for a tether to save mass is now

$$(1+\alpha)\tau + \tau_{IT} \;>\; \frac{\tau_d}{i_{av}} + \frac{\beta U_{orb} v_{IT}}{\eta_t} \;\equiv\; \tau_d\left[\frac{1}{i_{av}} + \frac{\beta\sigma_c E_m{}^2}{\alpha_t \rho}\frac{1}{\eta_t}\right]. \tag{31}$$

Here both η_t and i_{av} are functions of all three ratios L/L^*, $W_e/\sigma_c E_m{}^2 AL$ and L_i/L, and η_t decreases with increasing i_{av}. Minimum times are found to occur at large L/L^*, ratio $L_i/L \approx 1$ (with $L - L_i \sim L^*$), and $W_e/\sigma_c E_m{}^2 AL$ such that bias ΔV at the bottom of the tether is near zero, and depend on just the ratio $\beta\sigma_c E_m{}^2/\alpha_t\rho$ [23].

It follows from Eq. (6) that thrust with no power supply will result if $\overline{U}_{orb}$ is opposite $\overline{U}_{orb} - \overline{U}_{pl}$. This will allow, as recently suggested [24], [6], a no propellant/no power-supply mission to Jupiter, its *stationary* orbit lying well within its ionosphere.

8. POLAR DEORBITING

High inclination orbits pose a problem for ED tethers. The magnetic drag is then dramatically smaller than in case of low inclination orbits, because the geomagnetic component $B_\perp$ (off the orbital plane) is then small. With the average current in Eq. (26) being limited by the short-circuit current (proportional to $E_m = U_{orb}B_\perp$), the drag is quadratically small, and τ_d is quadratically large. It has been suggested that, for near-polar orbits, the tether be placed perpendicular to the orbital plane, $B_\perp$ (component perpendicular to both tether and orbital velocity) now being vertical; such tether (call it 'polar') has orbit-averaged $B_\perp$ about 10 times greater, and τ_d 100 times smaller, than corresponding values for usual, vertical tethers [25], [26].

The gravity gradient for a polar tether is compressive, however, as opposite a vertical one. The tether must now be rigid (a hollow boom), and thus somehow short to avoid buckling. This brings in new problems. *i*) A short tether collects little current, resulting in very small i_{av} values in (27) (current small against short-circuit current). *ii*) The induced bias is small, a power source being required, as with Ion Thrusters, to provide an (uniform) biasing voltage V_s. *iii*) Finally, and as seen below, the expellant mass consumed at the Hollow Cathode may not longer be neglected. Adding terms βW_e and $(1+\alpha)\dot{m}_{\exp}\tau$ to the right-hand-side of (25), it now reads

$$(1+\alpha)\tau + \tau_{IT} \; > \left[v_{IT}\frac{\alpha_t m_t}{F\tau}\left(1+\frac{\beta W_e}{\alpha_t m_t}\right) + \frac{v_{IT}}{\omega_{HC}L}\times\frac{I_{HC}}{I_{av}}(1+\alpha)\right]\tau\,, \tag{32}$$

where we wrote back $\tau_d / i_{av} \equiv \alpha_t m_t v_{IT}/F$ and defined a 'frequency' $\omega_{HC} \equiv B_\perp \times I_{HC}/\dot{m}_{\exp}$. State-of-the-art (*enclosed keeper*) Hollow Cathodes have a *current-to-mass flow rate* ratio that compares with the *charge-to-mass* ratio of a light ion. For $B_\perp \sim$ a fraction of gauss, and $L \sim 10$ km, $\omega_{HC}L$ is greater than v_{IT} by over two orders of magnitude.

Booms flat when rolled up on a drum and hollow/rigid when deployed have been validated in space and are easier to deploy than flexible tethers. For structural reasons boom thickness scales with cross-section perimeter p. A condition of no buckling of a thin-tube boom under the compressive gravity gradient, then requires *tube thickness* $\sim p \sim L^2$, leading to $m_t \sim L^5$. For any given *deorbiting mission impulse* $F\tau$, and assuming $\beta W_e/\alpha_t m_t$ small, the first and second terms in the right-hand-side of (32) scale as L^5 and $1/L$ respectively. The minimum system-mass thus occurs for a length L_{opt} such that the first term is $1/5$ the second one, and $L_{opt}^6 \sim F\tau$. Condition (32) at minimum, with $\alpha = 0.2$, $I_{av}/I_{HC} = 3/4$ (see below), now reads

$$(1+\alpha)\tau + \tau_{IT} \; > \; \frac{6}{5}\frac{I_{HC}}{I_{av}}(1+\alpha)\,\frac{v_{IT}}{\omega_{HC}L}\,\tau \;=\; 1.92\,\frac{v_{IT}}{\omega_{HC}L}\,\tau\,. \tag{33}$$

At low impulse, L will be too small to satisfy condition (33). At high impulse, collection will be reduced below the OML value because the cross-section will be too large ($p \sim L^2$). Also, from $I_{av}LB_\perp = F \sim L^6/\tau$ and $I_{av} \sim pL\sqrt{V_s}$, one has $\tau \sim L^2/\sqrt{V_s}$; to keep mission duration with impulse increasing would require to scale the supply voltage, $V_s \sim L^4$, resulting in a fast increasing power-subsystem mass,

$$\frac{\beta W_e}{\alpha_t m_t} = \frac{3\beta\sigma_c E_m{}^2}{8\alpha_t \rho}\left(\frac{V_s}{E_m L^*}\right)^{3/2} \sim L^4 \sim (F\tau)^{2/3}.$$

We note, however, that a narrow length-range covers a broad range in mission impulse.

Two bare booms of length ½L, one boom on each side, would be actually used in order to reduce the magnetic torque,. The component $B_\perp$ for a polar tether changes direction repeatedly in orbit, near the Equator. The current driven by the induced bias changes also direction as bias changes with $B_\perp$, but current driven by applied power will require a switch at the power source, to reverse the current. Each boom would carry a HC at its end; one (anodic) boom is polarized positive and collects electrons as a bare tether, with its HC idle or switched off, while the cathodic HC at the other end ejects electrons. This results in a ratio $I_{av}/I_{HC} = 3/4$, and some remnant (rotating) magnetic torque. Attitude control would be easier if the torque could be (nominally) made to vanish by fully balancing out the opposite boom torques. This could be achieved with minimum deorbit-performance by setting the HC's at distance $L/2\sqrt{3}$ from the spacecraft, average current then decreasing by a factor 0.72 .

If internal dissipation of energy is allowed, the stable attitude equilibrium of a spacecraft in its orbital frame requires the *minor axis* of inertia to lie vertical and the *major axis* along the perpendicular to orbit. A polar tether certainly does not satisfy that condition. Its attitude can be made stable by imposing a (Thomson) spin along the (tether) axis perpendicular to orbit, with value a few times the orbital angular velocity × the large *major*-to-*minor* moment of inertia ratio. Thomson equilibrium is useless, however, in case of strong dissipation, as with the 'whirling' instability (due to structural damping), if the spin exceeds the frequency ($\sim 1/L^{3/2}$) of the first vibrational mode. The Thomson spin increases with length as *tether mass* × $L^2 \sim L^7$, the threshold for the instability thus being a very sharp function of length L. Nonlinear effects, however, can saturate the 'whirling' instability; also, polar booms are not stringent as regards pointing/straightness.

9. AN UPPER ATMOSPHERE PROBE

A fully bare tape in LEO with current vanishing at both ends could serve as effective electron beam source to produce artificial auroras. Because of the large ion-to-electron mass ratio, the electrically floating tether is biased negative except over a $(m_e/m_i)^{1/3} \approx 0.03$ fraction of its length at the top. Ambient ions, impacting the tape with KeV energies and leaving as neutrals, liberate additional secondary electrons that race down the magnetic field and excite neutral molecules in the E-layer, resulting in auroral emissions. Observations along the beam, from a spacecraft carrying the floating bare-tether, might provide real-time mapping of neutral density in a critical altitude range, 110-150 km. The tether would operate at night-time with power supply from a solar array and a Hollow Cathode off; power and HC would be on at daytime to reboost the spacecraft once per orbit, making the tether an autonomous e-beam source. With no length L_i and the supply power determined by requiring thrust to fully balance drag, minimum system mass occurs at a definite value, L/L^* ($\propto L/\delta^{2/3}$) ≈ 20. With minimum system mass scaling as $wL\delta \propto wL^{5/2}$, and column-integrated ionization rates scaling roughly as $wL \times L$, a limited length range, $L \approx$ 15-25 km, might be allowed; this yields a thickness range 0.15-0.20 mm in L^*. Tape width w should be large to reduce the probability of cuts by debris but small enough to allow the tape to collect current in the OML regime. As alternative to tether day-thrusting, the solar array could feed power to an Ion thruster; for missions reaching beyond a few months, however, an Ion Thruster would always result in a heavier system because of the required propellant mass.

Each point in the tether emits monoenergetic secondary electrons, their energy and flux increasing linearly with distance h from the top, and their definite pitch-angle θ distribution involving the (dip) angle between magnetic line and horizontal plane; beam half-width perpendicular to the tether varies as $\sqrt{h}$. As beam electrons move in helical paths down magnetic lines, they find a density of neutral molecules increasing with decreasing altitude z. Beam electrons lose energy in inelastic ionization and excitation collisions, followed by photon emission. Electron energy at any altitude depends on the density profile above, the pitch angle, and the h value at emission, $\varepsilon = \varepsilon\,(z;\, h,\, \theta)$. Beam electrons are also scattered in elastic collisions with air molecules, which both affect pitch distribution and reduce beam flux by width-broadening due to diffusion across magnetic lines; simple, opposite models for the evolution in the pitch distribution show somewhat similar results for the pitch-averaged, volumetric ionization rate $\dot{n}_i\,(z, h)$. *Although the beam is 250m thick at most, the beam dwell-time at any particular* point does permit excited states with prompt emission through *allowed* transitions (lifetimes $\sim 10^{-7}$ s) to reach a steady-state, emission rates then being proportional to excitation rates. Since cross sections have similar energy dependence for all collisional interactions, there exist simple approximate relations between emission and ionization rates for prominent spectral bands and lines, under some standard conditions.

Observations from the spacecraft involve 'column'-integrated emission rates along straight lines extending over the ionization region and determining a relation $h\,(z,\, \psi)$; surface brightness b, at each small angle ψ from the magnetic field, mix altitude-z /h-value effects. As a result, the narrow emission footprint of the beam, which is tens of kilometers long and covers a line-of-sight range of about 6°, shows a peak in brightness that is about 10^2 *Rayleigh* for prominent bands and lines. For easier alignment, the angular field-of-view of a CCD camera could be taken as twice the angle subtended by the emission footprint, or about 12°; a tiled-detector with 10^3 30 μm-pixels per side of 30 mm, would then require a focal length of 15 cm. A brightness of 30-100 R would be well above background noise, and dark-current noise proves completely negligible; critical noise arises from the CCD readout. To get a large signal-to-noise ratio, the number of photons incident on a pixel must be large, requiring large pixels, a long exposure time, which is limited by satellite motion, and an entrance aperture subtending a large solid angle (*f*-ratio ~ 1).

Brightness of 30-100R could yield a charge packet of a few electrons per pixel. The image, though narrow across the footprint, would still cover about 5 pixels, a binning mode summing photons gathered by nearby pixels across the image with no increase in readout noise, to yield a 10-electron packet. The *S/N* ratio would still come out too low, however, even with recent techniques yielding sub-electron readout; a *S/N* ratio ~ 10^2 will require use of *Image Intensifiers*, which achieve net signal gains of about 1000. The camera would operate on the 391.4 nm (or the 427.8 nm) spectral band to determine the N_2 density, and the 777.4 nm and 844.6 nm lines, with definite branching ratios, to determine O and O_2 densities. A grating could perform a spectral separation of the incoming radiation, the narrow footprint then exhibiting 3 non-overlapping images at different wavelengths [27], [28].

Tomographic inversion will involve density values at a number of altitudes equal to the number of pixels along one side of the CCD detector, each pixel corresponding to a line-of-sight. An iterative solution scheme uses density values at step n in evaluating a $10^3 \times 10^3$ linearized kernel matrix, to determine densities at step $n + 1$. With the kernel numerically singular because of broadening that flattens considerably the peak in brightness versus line-of-sight, a (Singular-Value-Decomposition) regularization technique is required to proceed with inversion. A direct approximation to the actual density profile used as good initial guess to start the iteration, which would not converge otherwise, is first obtained by fitting parameters in a model and using a Direction Set (Powell) technique [29], [30].

10. ALFVEN WAVE FRONTS

A current-carrying ED-tether, in steady-state regime in the orbital frame ($\omega = k_x U_{orb}$, $\bar{k} \equiv$ *wavenumnber*), radiates waves with refraction index $n \equiv ck/\omega >> 1$. Only slow extraordinary (SE), fast magnetosonic or compressible Alfven (FM), and Alfven or shear Alfven (A), waves could then be radiated into the ionospheric cold-plasma. Conditions satisfied in LEO,

$$U_{orb} << V_A, \qquad m_i V_A^2 << m_e c^2, \qquad m_e V_A^2 << m_i U_{orb}^2, \tag{34}$$

where V_A is the Alfven velocity, determine the character of waves radiated. Both SE and FM radiation involve resonance ($k \to \infty$), nearly-electrostatic waves, with group velocity perpendicular to $\bar{k}$ in the $\bar{k} - \bar{B}$ plane. Those waves, in particular SE waves, are very weak; the SE-to-FM impedance ratio is $Z_{SE}/Z_{FM} = ½(m_e/m_i)^{1/2}$. We also have (for the simplest case of electrical contact at tether ends)

$$I Z_{FM} = \sqrt{\frac{m_i U_{orb}^2}{2} \frac{kT_e}{\pi} \frac{1}{e}} \approx 0.38 \text{ V}, \tag{35}$$

which is again very small for the high currents of interest.

The Alfven impedance is itself small ($\omega_{ci} \equiv$ ion cyclotron frequency),

$$Z_A = \frac{V_A}{c} \frac{\ln(\omega_{ci} L / U_{orb}) + \ln 2 + \gamma - 1}{2\pi\varepsilon_0 c} \qquad (\gamma \approx 0.57); \tag{36}$$

the group velocity is here along $\bar{B}$, with $\bar{k}$ near perpendicular to $\bar{B}$. A linearized analysis of the Alfven radiation further proves that, far from the tether, most power is carried in the 'Alfven wings' behind the wave-front. The near wave-front, however, would require a nonlinear description, particularly for high signals [31], [32].

Large signals will require modulating the current. If the current is large enough, so will be the magnetic field generated by the tether current itself. One would then have a background magnetic-field time modulated at some frequency ω_{mod}. Such field may excite a left-hand (LH) circularly polarized, growing Alfven wave at frequency $½\omega_{mod}$ and wave number $k_1 = ½\omega_{mod}/V_A$, which propagates along the field. An analysis of the derivative nonlinear Schrödinger (DNLS) equation, often used to describe Alfven wave-fronts as at the Earth's bow shock, proves that such growing wave may couple to two other L-H circularly polarized waves with wavenumbers $k_3 + k_2 = 2k_1$, that show chaotic behavior within some definite range for the ratio k_3/k_2 [33].

11. CONCLUSION

A first bare-tether power generation experiment was A-recommended (Heidelberg, March 1992) by an external panel of ESA for the *Columbus Precursor Flights* but exposed tests were cancelled later that year. A deorbiting mission (ProSEDS) resulting from a White Paper to NASA (late 1995) on bare-tether use on the ISS, to fly on March 29, 2003, was cancelled following the Columbia accident. At present, tests on bare-tether collection and auroral effects on board a sounding rocket are being planned.

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